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The photoionization effect of the ultraviolet background on the colour-magnitude relation of elliptical galaxies

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ABSTRACT

We examined effects of the ultraviolet background radiation (UVB) on the colour–magnitude relation (CMR) of elliptical galaxies in clusters of galaxies in the hierarchical clustering scenario by using a semi-analytic model of galaxy formation. In our model the UVB photoionizes gas in dark haloes and suppresses the cooling of the diffuse hot gas onto galaxy discs. By using a semi-analytic model without the effect of the UVB, Kauffmann & Charlot found that the CMR can be reproduced by strong supernova heating because such supernova feedback suppresses the chemical enrichment in galaxies especially for small galaxies. We find that the CMR also becomes bluer because of the UVB, in a different way from the effect of supernova feedback. While the supernova feedback suppresses the chemical enrichment by a similar mechanism to galactic wind, the UVB suppresses the cooling of the hot gas. This fact induces the suppression of the metallicity of the intracluster medium (ICM). In our model we find that the existence of the UVB can plausibly account for an observed ICM metallicity that is equal to nearly 0.3 times the solar value, and that in this case we can reproduce the CMR and the metallicity of the ICM simultaneously.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – large-scale structure of the Universe.

1 INTRODUCTION

It is well known that elliptical galaxies in clusters of galaxies have a tight correlation between their colours and magnitudes (so-called ‘colour–magnitude relation’; hereafter CMR). For example, the rms scatter about the mean CMR is typically ~ 0.04 mag in the Virgo and Coma clusters of galaxies. It is equivalent to observational errors (Bower, Lucey & Ellis 1992). Because it is believed that this tight relation reflects formation and evolution processes of elliptical galaxies, many people have studied this relationship in order to understand galaxy formation processes.

The traditional scenario of formation of ellipticals is that a monolithic protogalactic cloud collapses and then forms stars over a short time-scale until the formation of a galactic wind (Larson 1974; Arimoto & Yoshii 1986, 1987). In this framework, Kodama & Arimoto (1997) found that the CMR is corresponding to the sequence of the mean stellar metallicities (the *metallicity sequence*) by comparing the CMRs of high redshift cluster galaxies with those of theoretical models based on the traditional scenario. This fact that the CMR is a metallicity sequence was also confirmed by investigating photometric properties of the stellar populations of ellipticals (Ferreras, Charlot & Silk 1999).

In contrast to the collapse/wind model, recent developments on both theory and observation of the cosmological structure formation are revealing that objects such as galaxies and clusters of galaxies are formed through hierarchical clustering of smaller objects. Kauffmann & Charlot (1998; hereafter KC) applied their semi-analytic model to the problem of the CMR and reproduced the observed CMR when the model includes the chemical evolution process and strong feedback to interstellar media by supernovae. Moreover, they found a tight luminosity–metallicity relation and reproduced other properties of cluster ellipticals such as the line indices and the Faber-Jackson relation.

KC interpreted why the CMR is reproduced when the feedback process is strong as follows; they considered that giant ellipticals must be formed by mergers of larger spiral galaxies and that dwarf ellipticals must be formed from smaller spirals. Because the feedback strength depends on the mass of galaxies, the metallicity of stars in more massive progenitors becomes higher than that in smaller progenitors.

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Therefore giant ellipticals become redder than dwarf ellipticals.

In this work, we introduce the photoionization process of galactic gas by the UV background radiation (UVB) in our model. We have already investigated the effect of the UVB on the luminosity function and the colour distribution of galaxies (Nagashima, Gouda & Sugiura 1999), and here investigate this effect on the CMR, which has not been considered. Moreover, it is also shown how the metal abundance in the intracluster medium (ICM) is affected by the UVB. Through this work, the difference between the mechanisms and effects of the supernova feedback and the UVB in the galaxy formation process will be clarified.

In Section 2, we describe the semi-analytic model used here briefly. In Section 3, we show the CMR and show that the effect of the UVB seems similar to the effect of the supernova feedback. In Section 4, we investigate the property of the effect of the UVB on the CMR. We will show that the CMR hardly depends on the intensity of the UVB if it is sufficiently strong, and interpret this result physically by using a simple model. In Section 5, the metal abundance of the ICM is discussed. Section 6 is devoted to conclusions.

2 MODEL

Here we describe the semi-analytic model that we use briefly. At first, merging histories of dark haloes are realized by the extension of the Press-Schechter formalism (Press & Schechter 1974). We adopt a method given by Somerville & Kolatt (1999). The cosmological model is fixed to a cosmological constant-dominated flat universe, $\Omega_0=0.3, \Omega_\Lambda=0.7, h=0.7$ and $\sigma_8=1$, where h is the Hubble parameter, $h\equiv H_0/100$km s^{-1}Mpc^{-1}, and σ_8 is the normalization of the power spectrum of density fluctuation. We use a power spectrum given by Bardeen et al. (1986). Haloes with circular velocity smaller than 40km s^{-1} are treated as diffuse matter. In this paper, we consider haloes only with circular velocity $V_{\rm c}=10^3$ km s^{-1} at $z=0$, which is a typical value for a cluster of galaxies.

Next, in the merging path, we calculate the evolution of the baryonic component from higher redshift to present. Diffuse gas in a newly collapsing dark halo is heated up to the virial temperature of the dark halo by shock heating (the *hot gas*). The shock heating occurs only in the case that the mass ratio of the largest progenitor among all progenitors of the halo to the newly collapsing halo exceeds $f_{\rm reheat}$. In the other case, the hot gas in the new halo conserves the temperature of the largest progenitor. If the new halo has no progenitor halo, the mass fraction of the hot diffuse gas is equal to $\Omega_{\rm b}/\Omega_0$. Here we use $\Omega_{\rm b}=0.015h^{-2}$. Assuming the singular isothermal density distribution of the hot gas, we calculate the cooled gas mass by equating the cooling time-scale $\tau_{\rm cool}(r)$ to the elapsed time from the last shock heating $t_{\rm elapse}$, $\tau_{\rm cool}(r_{\rm cool})=t_{\rm elapse}$, where the cooling function given by Sutherland & Dopita (1993) is used. If the UVB does not exist, the gas within the cooling radius, $r_{\rm cool}$, cools and is accreted by a disc of the halo central galaxy. In the other case, the UV photons penetrate the cooled gas from $r_{\rm cool}$ to $r_{\rm UV}$, where $r_{\rm cool}>r_{\rm UV}$, and the outer layer $r>r_{\rm UV}$ is photoionized. This $r_{\rm UV}$ is estimated by assuming the inverse Strömgren sphere approximation (Nagashima et al. 1999). Thus the gas within $r_{\rm UV}$ is cooled. In this paper, we assume that the intensity of the UVB, J, evolves as $J\propto(1+z)^\gamma$, where $\gamma=4$ for $z\le 2$ and $\gamma=-1$ for $2<z\le 6$. The UVB does not exist before $z=6$. We found that the results in this work does not depend on the shape of the intensity evolution of the UVB qualitatively. In the following, we parameterize the UV intensity at $z=2$ by $J_{-21}\equiv(J/10^{-21}{\rm erg~cm^{-2}s^{-1}Hz^{-1}sr^{-1}})$. It should be noted that in the case where the circular velocity of haloes exceeds 500 km s^{-1}, we prevent the cooling process manually. This is the same procedure as Kauffmann, White & Guiderdoni (1993).

Stars are formed from this cold gas. The star formation rate in discs is given by $\dot{M}_*=M_{\rm cold}/\tau_*$, where M_* and $M_{\rm cold}$ are the masses of the stars and cold gas, respectively, and τ_* is the star formation time-scale. We adopt a similar form to that given by KC, $\tau_*=\tau_*^0[\tau_{\rm dyn}/\tau_{\rm dyn}(z=0)]$, where $\tau_{\rm dyn}$ is the dynamical time-scale of the halo which is calculated by the spherical collapse approximation (Tomita 1969; Gunn & Gott 1972), and τ_*^0 is a free parameter, which is set to 2Gyr in this paper.

With star formation, supernovae occur and heat up the surrounding cold gas to the hot phase (supernova feedback). The reheating rate is given by $\dot{M}_{\rm reheat}=\beta(V_{\rm c})\dot{M}_*$, where $\beta(V_{\rm c})=(V_{\rm c}/V_{\rm hot})^{-\alpha_{\rm hot}}$, $V_{\rm hot}$ and $\alpha_{\rm hot}$ are free parameters, respectively. This is the same parameterization given by Cole et al. (1994), and we adopt $\alpha_{\rm hot}=2$ according to KC.

Chemical enrichment is solved in a consistent way to the above star formation process. The yield y is assumed to be twice the solar value according to the strong feedback model of KC. While KC assumed that a fraction f of metals is released from ejecta of the supernovae to the hot gas directly, we do not assume such a process. The metals are released to the hot gas by the supernova feedback in the same way as for the cold gas.

We recognize a system consisting of the stars and cooled gas as a *galaxy*. Hereafter we define the mass of a galaxy as the mass of stars and cold gas of the galaxy. When two or more dark haloes merge together, there is a possibility that galaxies contained in progenitor haloes merge together. We define a central galaxy as the central galaxy of the largest progenitor halo. Other galaxies are defined as satellite galaxies. When the elapsed time of a galaxy from the epoch at which the galaxy becomes satellite exceeds the dynamical friction time-scale of the halo, the galaxy merges with the central galaxy of the halo. When galaxies merge together, if the mass ratio of the smaller galaxy to the larger galaxy exceeds $f_{\rm bulge}$, starburst occurs and all cold gas is consumed. The same feedback law as that for discs is adopted. Then, all of stars becomes bulge stars. In the other case, the smaller galaxy merges into the disc component of the larger galaxy without any additional star formation activity. In this paper we adopt $f_{\rm bulge}=0.2$.

Finally, we calculate the colour and luminosity of each galaxy from star formation history of each galaxy by using the stellar population synthesis technique. We use a simple stellar population model given by Kodama & Arimoto (1997). Through the above procedures, we obtain a colour-magnitude diagram of galaxies. In the follows, we pick out galaxies with the B-band bulge-to-disc luminosity ratio

larger than 1.52 as elliptical galaxies according to Simien & de Vaucouleurs (1986).

The above procedure is mainly based on Kauffmann et al. (1993), Cole et al. (1994, 2000) and Somerville & Primack (1999). Though the details of our model are slightly different from the previous ones, we confirmed that the main results of the previous work, such as both of the field and cluster luminosity functions, colour distribution and cold gas mass fraction of galaxies, are almost reproduced by our model within similar range of values of the parameters (Nagashima & Gouda, in preparation).

3 COLOUR-MAGNITUDE RELATION

In Figure 1, we show the colour-magnitude diagram for four models. The thick solid curves with errorbars indicate the CMRs given by the models averaged over 50 realizations. The errorbars denote the mean values of 1σ scatter for each realization, so they are corresponding to the scatter for each cluster of galaxies. Dots indicate ellipticals only for five realizations. The thin dashed lines indicate the observational CMR in the Coma cluster (Bower, Lucey & Ellis 1992) and the thin solid lines denote the aperture-corrected CMR in the Coma cluster (Kodama, Arimoto, Barger & Aragón-Salamanca 1998). Since colour of each elliptical galaxy in our model is integrated over the whole region of the galaxy, the model CMR should be compared with the aperture-corrected CMR. Upper panels show the models without the UVB and lower panels show those with the UVB of $J_{-21}=0.1$.

As shown by KC, when we do not consider the effect of the UVB, the model with $V_{\rm hot}=280$ km s^{-1} can reproduce the observed CMR (Figure 1a). Imposing stronger feedback with $V_{\rm hot}=350$ km s^{-1}, the colours of ellipticals become too blue to be consistent with the observation (Figure 1b) because the metallicity of ellipticals decreases (see next section). The same effect of the bluing is also caused by the UVB. In Figure 1c, we show the model with the same value of $V_{\rm hot}$ as that of the model in Figure 1a and with the UVB of $J_{-21}=0.1$. By weakening the feedback strength from $V_{\rm hot}=280$ to 220km s^{-1}, we obtain a CMR in agreement with the observation again (Figure 1d). This manipulation is corresponding to reverse of the procedure from Figure 1a to 1b. Thus we obtain a similar CMR to the observation with both of the weaker feedback and the UVB.

It should be noted that KC found that the CMR reflects the metallicity-luminosity relation. We also find that models with similar CMR show similar metallicity-luminosity relation independent of the existence of the UVB, e.g., the differences of the metallicity-luminosity relations between the models of Figures 1a and 1d and between Figures 1b and 1c are negligible. Thus the above properties of the CMR, i.e., the dependences on the supernova feedback and on the UVB, are related with the stellar metallicity of ellipticals. In this connection, we find that the shape of the metallicity-luminosity relation of the four models is similar to the metallicity sequence of Kodama & Arimoto (1997), in spite of the significant difference between our model and their monolithic cloud collapse model. This also suggests the importance of investigating the chemical enrichment process of galaxies.

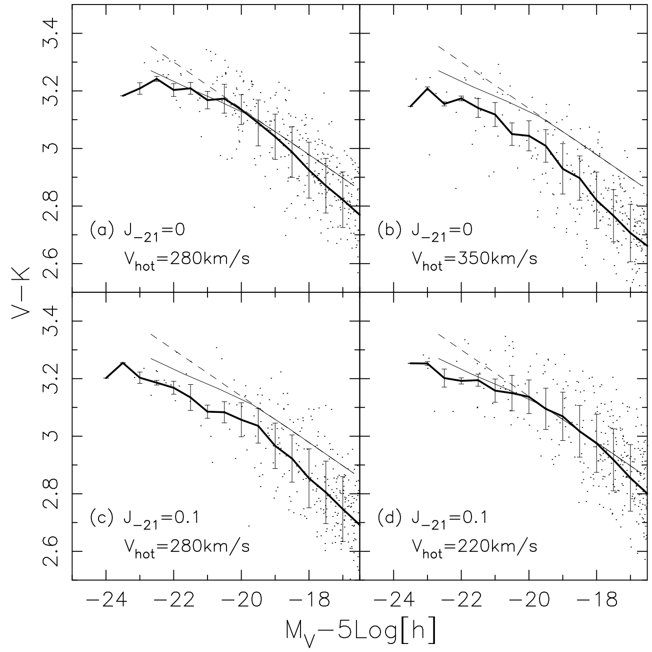

Figure 1. $V-K$ Colour–magnitude diagram. The thick solid curves with errorbars denote the model CMRs averaged over 50 clusters and the errorbars denote the mean values of the 1σ scatter for each realization. Each dot indicates an elliptical galaxy only for five realizations. The thin dashed line in each panel indicates the CMR in the Coma cluster (Bower et al. 1992). The thin solid line denotes the aperture-corrected CMR in the Coma (Kodama et al. 1998). Model parameters for the four models are shown in Table 1. Upper panels: $J_{-21}=0$. (a) $V_{\rm hot}=280$ km s^{-1}. (b) $V_{\rm hot}=350$ km s^{-1}. Lower panels: $J_{-21}=0.1$. (c) $V_{\rm hot}=280$ km s^{-1}. (d) $V_{\rm hot}=220$ km s^{-1}. Note that the simulations presented in (a) and (c) have the same strength of the supernova feedback.

4 CHEMICAL ENRICHMENT OF GALAXIES

While the above result seems to show that the effect of the UVB is the same as the supernova feedback apparently, the ways to make ellipticals metal-poor are different. In Figure 2a, we show four CMRs with different strengths of the UVB, $J_{-21}=0.01, 0.1, 1$ and 10 and with the same feedback strength, $V_{\rm hot}=280$ km s^{-1}. The CMRs are hardly changed by the UVB if $J_{-21}\geq 0.1$. On the other hand, the luminosity functions are clearly affected by the UVB. In Figure 2b, we show the cluster luminosity functions of these models. The thin solid line denotes the observational cluster luminosity function in the Virgo cluster given by Sandage et al. (1985). These figures show that the sufficiently strong UVB decreases the number of galaxies by its photoionization effect while it does not affect the metallicity of each elliptical galaxy.

In the following, we explore the reason why the metallicity does not depend on J_{-21}. First of all, we evaluate the effect of the supernova feedback. The mass-weighted mean metallicity of each galaxy is given by (Nagashima & Gouda, in preparation)

$$\langle Z_*(t)\rangle_{M_*}= \\ 1-F\frac{1-\exp\left[-(1+\beta-(R-\alpha y)(1-f))\frac{t-t_s}{\tau_*}\right]}{1-\exp\left[-(1+\beta-R(1-f))\frac{t-t_s}{\tau_*}\right]}, \quad (1)$$

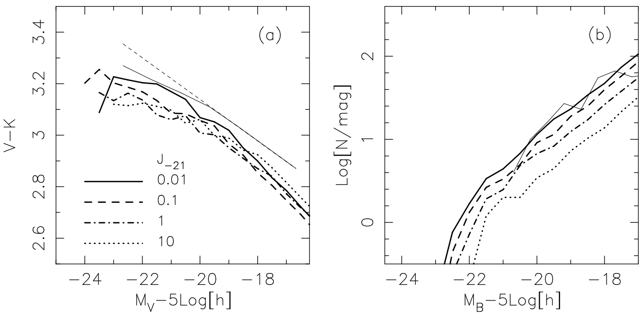

Figure 2. (a) Colour–magnitude relations. Model parameters of these four models are the same as those of Figure 1c ($V_{\rm hot} = 280$ km s^{-1}) but for the intensity of the UVB. The solid, dashed, dot-dashed and dotted lines denote the models with $J_{-21} = 0.01, 0.1, 1$ and 10, respectively. (b) Cluster luminosity functions. The types of lines are the same as (a). The thin line is the luminosity function of the Virgo cluster galaxies by Sandage et al. (1985).

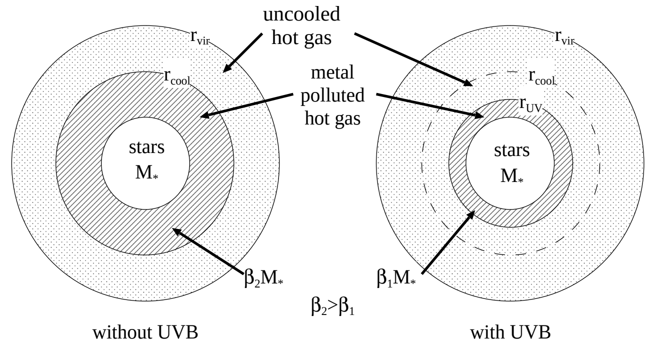

Figure 3. Schematic descriptions of ellipticals in dark haloes. These two galaxies have the same masses of dark matter and stars. $r_{\rm vir}$ denotes the virial radius of the haloes. The mass of the reheated, metal-polluted hot gas is βM_*. The right model has weaker supernova feedback than the left model because of the UVB.

where

$$F = \frac{1 - Z^0_{\rm cool}}{1 + \frac{(1-f)\alpha y}{1+\beta-R(1-f)}}, \tag{2}$$

α is a locked-up mass fraction, $\alpha = 1 - R$ (R is the gas fraction returned by evolved stars), and $Z^0_{\rm cool}$ is an initial metallicity of cold gas at $t = t_s$, where $t_{\rm s}$ is an initial time. In this paper, $f = 0$ and $R = 0.25$. The starburst corresponds to $t/\tau_* \to \infty$, so the final stellar metallicity depends only on the strength of the supernova feedback, β, as

$$\begin{aligned} \langle Z_*(t\to\infty)\rangle_{M_*} &= \frac{(1-Z^0_{\rm cool})\alpha y}{1+\beta-R+\alpha y} + Z^0_{\rm cool} \\ &\simeq \frac{y}{1+\beta} + Z^0_{\rm cool}. \end{aligned} \tag{3}$$

Therefore the stronger the feedback is, the lower the metallicity is. Thus the differences between Figures 1a and 1b and between Figures 1c and 1d are explained by the strength of the supernova feedback, β.

Next we investigate the process by which the UVB suppresses the metallicity. When the UVB exists, the amount of the cooled gas decreases. Then the amount of the metal polluted reheated gas also decreases and the metallicity of the hot gas is suppressed. The hot gas, including metal polluted reheated gas, cools at the later stage again. Therefore the metallicity of the re-cooled gas decreases. This corresponds to decreasing $Z^0_{\rm cool}$ at the later stage in eq.(3). Thus the mean stellar metallicity is suppressed by the UVB. If the UVB is sufficiently strong ($J_{-21} \gtrsim 0.1$), then $Z^0_{\rm cool}$ becomes negligible compared with the first term in eq.(3), $y/(1+\beta)$. As a result, the metallicity does not depend on the J_{-21}.

5 METAL ABUNDANCE OF INTRACLUSTER MEDIUM

As considered in the previous section, the UVB may affect the metallicity of the hot gas. Here we investigate it by a simple model. Now consider two ellipticals with the same stellar mass which are illustrated in Figure 3. One is exposed to the UVB (right in Figure 3) and the other is not (left).

Table 1. Metallicity of intracluster medium

Model	$V_{\rm hot}$ (km s^{-1})	J_{-21}	$Z_{\rm ICM}/Z_\odot$
Figure 1a	280	0	0.59± 0.01
Figure 1b	350	0	0.49± 0.01
Figure 1c	280	0.1	0.34± 0.02
Figure 1d	220	0.1	0.38± 0.02

The second case is required to have stronger feedback (β_2) than the first (β_1) because the same mass of stars must be formed from larger amount of cold gas than in the first case. Thus the second elliptical has larger amount of the metal polluted reheated gas than the first one.

From the above discussion, we expect that the metal abundance of the ICM of the first elliptical should become smaller than that of the second elliptical. We show the metallicity of the ICM, $Z_{\rm ICM}$, in Table 1 for the four models in Figure 1. $Z_{\rm ICM}$ decreases significantly when the UVB exists. Because of $Z_{\rm ICM} \simeq 0.3 Z_\odot$ in some observations (e.g., Tamura et al. 2001), the existence of the UVB can plausibly account for the metallicity of the ICM. It should be noted that KC also obtained $Z_{\rm ICM} \simeq 0.3$ with a non-zero value of f without the effect of the UVB. Their model is nearly corresponding to our model with $f_{\rm reheat} \to 0$, in which we find $Z_{\rm ICM} \simeq 0.3$ with no UVB. Thus our model is not inconsistent with KC. At present there is no method of determining the value of the parameter $f_{\rm reheat}$, although Salvador-Solé, Solanes & Manrique (1998) suggest $f_{\rm reheat} \sim 0.6$ by comparing the so-called universal density profile of dark haloes (Navarro, Frenk & White 1996) with the theoretical prediction using both of the spherical collapse model and the formation redshift distribution of haloes. Thus we consider that models with $f_{\rm reheat} \simeq 0.5$ are more realistic.

6 CONCLUSIONS

We investigate the effect of the UVB on the CMR in the hierarchical clustering scenario by using a semi-analytic galaxy formation model, in which we introduce the photoionization

effect of the gas by the UVB. We show that the UVB plays a similar role on the CMR to the supernova feedback apparently. Both effects suppress the mean stellar metallicity of each elliptical galaxy. Therefore the CMR becomes bluer in the both cases.

We find that the CMR is affected even if the UV intensity is weak, $J_{-21} \sim 0.1$ and hardly depends on the intensity in the case of sufficiently strong UVB, $J_{-21} \gtrsim 0.1$, in contrast to the supernova feedback. This is because the UVB suppresses only the cooling process (see below). Moreover we show that the two mechanisms which degenerate in the CMR can be distinguished by investigating the metallicity of the ICM, and that the existence of the UVB is favoured to account for the observed metal abundance of the ICM. It will be possible to detect the difference in the metallicity by observational studies with *XMM-Newton*.

The physical mechanisms affecting the CMR of the UVB and of the supernova feedback are different, as follows. In the case of the strong feedback without the UVB, while much cold gas is reheated before metal-rich stars are formed, much metal-polluted gas is expelled in the form of hot gas such as the galactic wind. On the other hand, the UVB suppresses gas cooling. So the material forming stars, that is, the cooled gas, is less than in the former no UVB case. Under the UVB scenario, if the supernova feedback is weaker than the former no UVB case, a similar mass of stars can be formed from a smaller amount of the cooled gas, and then the stars are chemically enriched. Note that in the case of a UVB the hot gas becomes metal-poor because a smaller fraction of metals is expelled from galaxies than in the former case. Thus conserving the stellar metallicity of each galaxy by introducing the UVB and weakening the feedback, the metal abundance in the ICM can become lower compared to the former case of no UVB.

Recently an overcooling problem has been discussed by using high-resolution hydrodynamical simulations (Balogh et al. 2001), in which too much gas cools compared with observations. The effect of the UVB, as well as strong supernova feedback, will be useful to help solve this problem. Besides by using the proximity effect, it is suggested $J_{-21} \gtrsim 1$ (Jennifer et al. 2000). In this paper, we showed that the UVB affects the CMR and the ICM even in the case of $J_{-21} \gtrsim 0.1$, but considered the effect of the UVB only by introducing the simple inverse Strömgren sphere approximation. Hence these results mean that we should investigate the effect of the UVB in more detail. While we believe that we can understand the effect of the UVB qualitatively, detailed radiative transfer calculation will be required for quantitative estimation of the effect.

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